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# **Molecular Beam Epitaxy Growth and Characterization of Thin Layers of Semiconductor Tin**

**by P Folkes, P Taylor, C Rong, B Nichols, H Hier,  
and M Neupane**

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*Sensors Electron and Devices Directorate, ARL*

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## 1. Introduction

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In recent years, there has been strong research interest in semiconductor tin ( $\alpha$ -Sn) due to theoretical predictions that, depending on its thickness,  $\alpha$ -Sn is a 3-D or 2-D topological insulator (TI). Three-dimensional TIs are electronic materials that have a bulk bandgap and gapless conducting surface states that are protected by the topological and symmetry characteristics of their bandstructure.<sup>1</sup> One of the fundamental characteristics of 3-D TIs is the occurrence of gapless surface states where the conduction band and the valence band touch each other at distinct points in the Brillouin zone, called Dirac points. Near those points the electronic energy-momentum dispersion is similar to the linear dispersion of massless relativistic electrons described by the Dirac equation.<sup>1</sup> Two-dimensional TIs exhibit spin-filtered ballistic transport in edge channels where the up-spins propagate in one direction, while the down-spins propagate in the opposite direction at low temperatures and elastic backscattering is suppressed in the absence of magnetic impurities. These results suggest the possible realization of room-temperature electrical conduction without dissipation in the edge channels of 2-D TIs with a large bandgap and applications in TI-based, energy-efficient devices.<sup>2</sup>

Recent theory<sup>3</sup> has predicted that a monolayer tin film (stanene) is a 2-D TI with a bulk bandgap up to 0.3 eV, which is sufficiently large for practical applications at room temperature. This theoretical prediction has not been observed, because the growth of 2-D tin film has not been achieved. Bulk single-crystal  $\alpha$ -Sn is a zero-bandgap semiconductor that is stable at temperatures lower than 286 K and undergoes a phase transition at 286 K to metallic tin ( $\beta$ -Sn), the stable tin allotrope at temperatures above 286 K.<sup>4</sup>

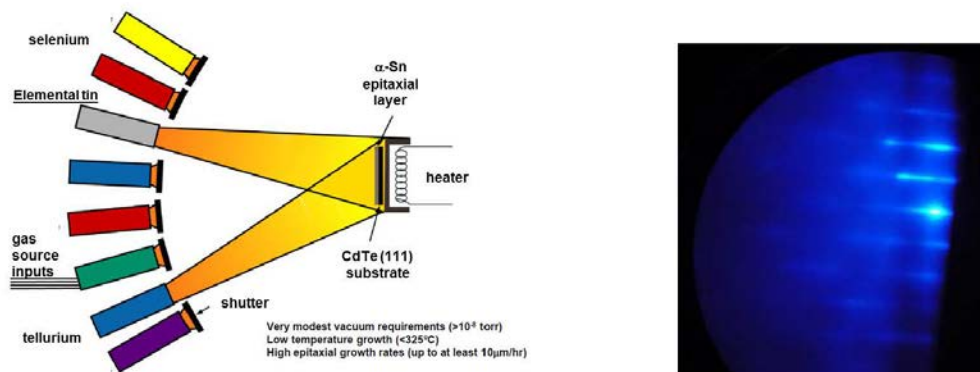
High-quality, single-crystal layers of slightly strained  $\alpha$ -Sn that are predicted to be 3-D TIs<sup>5,6</sup> were grown by molecular beam epitaxy (MBE)<sup>7</sup> on indium antimonide and cadmium telluride (CdTe) substrates at room temperature. The MBE-grown layers of  $\alpha$ -Sn are stabilized by the substrate and undergo a transition to  $\beta$ -Sn at around 390 K. Raman scattering from single-crystal and polycrystalline bulk tin has been reported<sup>8,9</sup> In this report, we present results of a study of the MBE growth and Raman scattering characterization of thin layers of  $\alpha$ -Sn.

## 2. Experimental

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The MBE growth of  $\alpha$ -Sn was accomplished at the unusually low substrate temperature of  $-20$  C. The schematic layout of the MBE is shown on the left panel of Fig. 1. High-purity elemental tin metal was used for the growth of  $\alpha$ -Sn. The only other source material used is elemental Te, which was only used during a brief

thermal cleaning of the CdTe substrate. Before loading into the MBE, the CdTe substrates were etched using a dilute bromine-methanol solution, which leaves a somewhat protective Te-rich surface.<sup>10</sup> Once the substrates were loaded into the MBE, they were thermally cleaned to remove the protective Te-rich layer by heating the substrate above 450 °C.



**Fig. 1** (Left) Schematic layout of MBE for the growth of  $\alpha$ -Sn/CdTe (111) and (right) the reflection high-energy electron diffraction (RHEED) pattern confirming epitaxial growth of  $\alpha$ -Sn on CdTe (111) at 253 K

A small overpressure of Te in the form of Te dimers ( $\text{Te}_2$ ) was maintained on the surface during the high-temperature heating to preserve proper 1:1 Cd-to-Te stoichiometry. After the tellurium-rich protective layer was thermally removed from the surface, a pristine zincblende CdTe surface is obtained. In bulk form, the  $\alpha$ -Sn phase is stable at temperatures below about 14 °C. To enhance the growth of the diamond cubic  $\alpha$ -Sn phase, the thermally cleaned CdTe substrates were cooled to the unusually low growth temperature of 253 K (−20 °C). The tin source material was heated in a standard MBE effusion cell to obtain a tin molecular beam that has a deposition rate of 0.04  $\mu\text{m}/\text{h}$ . MBE growth was initiated on the pristine CdTe at 253 K by opening the shutter and directing the molecular beam of tin at the CdTe substrate. Successful epitaxial growth was confirmed by the obtained diffraction pattern using reflection-high-energy-electron-diffraction (RHEED), as shown on the right panel of Fig. 1. Although MBE growth of  $\alpha$ -Sn has been previously been reported for (001) CdTe, this is the first demonstration of (111) MBE growth on (111) CdTe.<sup>7</sup>

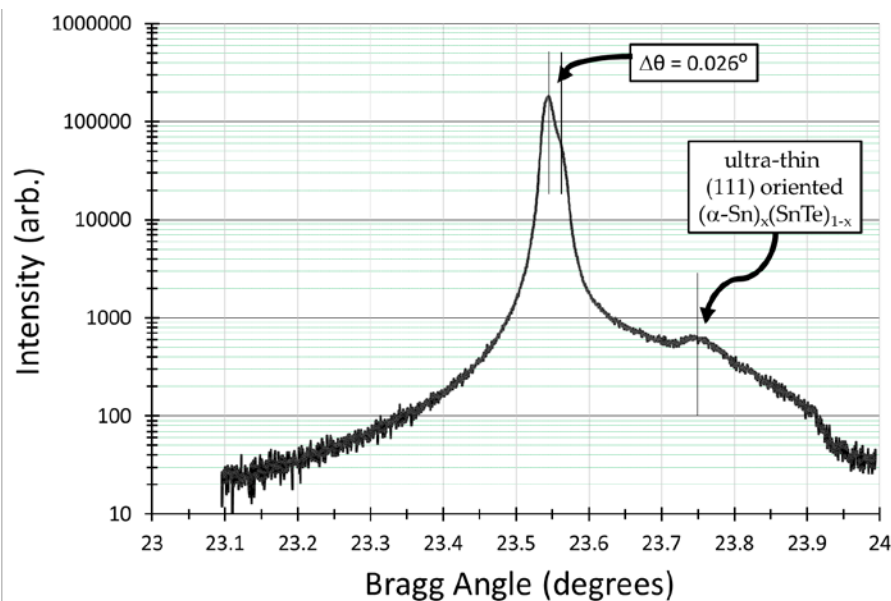
A Witec alpha 300a spectrometer was used to detect the Raman scattering spectra with resolution of 0.9  $\text{cm}^{-1}$  at 300 K in the backscattering geometry using a 1-mW, 532-nm laser. An incident laser power of 1 mW and a measurement time of 10 s was used to avoid sample heating. The  $\alpha$ -Sn layers were also characterized with high-resolution X-ray diffraction, Hall, and atomic force microscopy (AFM) measurements.

### 3. Results

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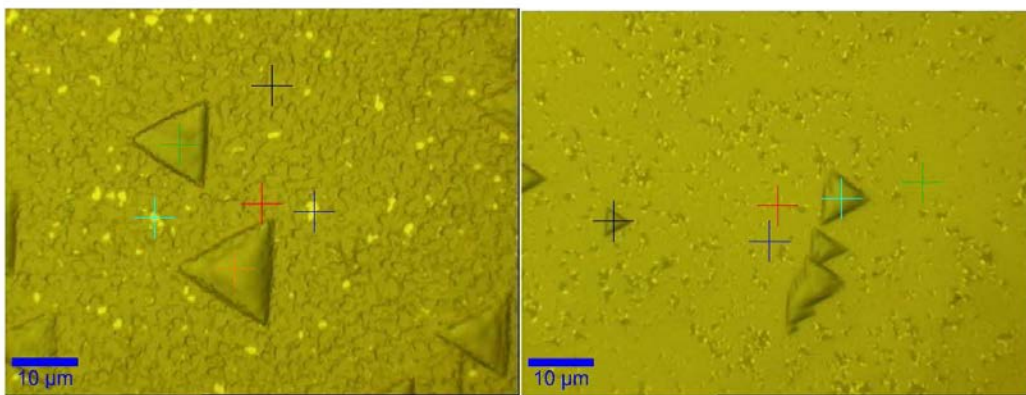
The high-resolution X-ray diffraction spectrum of the epitaxial  $\alpha$ -Sn/CdTe (111) is presented in Fig. 2. The thickness of the epitaxial layer is 20 nm. There are several important points that are indicated:

- 1) The spacing between the (111) diffraction peaks of  $\alpha$ -Sn and CdTe is 0.026. This is evidence for very small strain between the  $\alpha$ -Sn epitaxial layer and the CdTe substrate. The unstrained lattice parameter for CdTe is 0.6482 nm and the unstrained lattice parameter for  $\alpha$ -Sn is 0.6489 nm. Assuming zero strain and using the respective (111) reflections of the unstrained materials, the predicted difference between the peaks should be 0.027, which is within experimental error of the experimental observation.
- 2) There appears to be an ultra-thin interdiffused alloy layer of  $(\alpha\text{-Sn})_x(\text{SnTe})_{1-x}$ . The evidence that supports that is shown as the small diffraction peak at a slightly larger diffraction angle of  $23.75^\circ$ . Tin-telluride (SnTe) has an unstrained lattice constant of 0.630 nm. If the SnTe were pure, the position of the (111) diffraction peak should be located at  $24.44^\circ$ . Also, if there was a pure, coherently strained layer, it would be in a strongly tensile state of strain, which would cause the Bragg diffraction peak to shift to even larger than  $24.44^\circ$ . Because the peak is broad and shifter to a smaller angle, this indicates an expansion of the lattice, which is likely caused by the formation of an alloy of SnTe with  $\alpha$ -Sn whose lattice constant is larger. The formation and presence of this alloy layer can be explained by the presence of adventitious Te that resides on the surface after thermal cleaning of the CdTe substrate under a Te overpressure. Because the intensity is more than 2 orders of magnitude weaker than the main Bragg peaks, the layer must be ultra-thin with respect to the thickness of the  $\alpha$ -Sn, and likely has thickness on the scale of monolayers, approximately 1 nm.



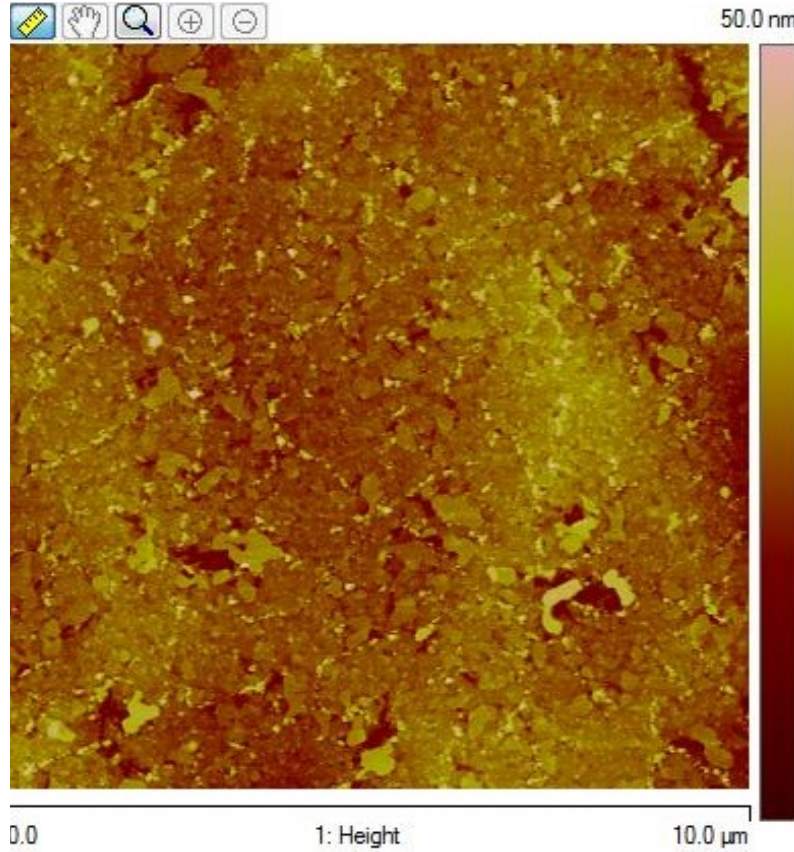
**Fig. 2** X-ray diffraction spectrum from 20-nm-thick epitaxial  $\alpha$ -Sn/CdTe (111)

Preliminary Hall effect measurements indicate that the  $\alpha$ -Sn layers are p-type with a hole concentration of  $2 \times 10^{18} \text{ cm}^{-3}$  and a mobility of  $400 \text{ cm}^2/\text{Vs}$ . Micron-scale photographs of the surface of a 1000- and 200-Å MBE-grown layer of  $\alpha$ -Sn obtained using a 100 $\times$  microscope lens are shown in Fig. 3. Triangular-shaped etch pits from the etched CdTe substrates are observed in both surfaces. The size and density of these etch pit defects depends on the quality of the CdTe substrate and the substrate cleaning procedures. These etch pits do not significantly affect the MBE growth of  $\alpha$ -Sn. The 1000-Å layer exhibits more CdTe substrate surface roughness and larger etch pits compared to the 200-Å layer, but this does not prevent the heteroepitaxial growth of  $\alpha$ -Sn over essentially the entire CdTe buffer layer.



**Fig. 3** Photograph of the surface of a 1000-Å (left) and 200-Å (right) layer of  $\alpha$ -Sn

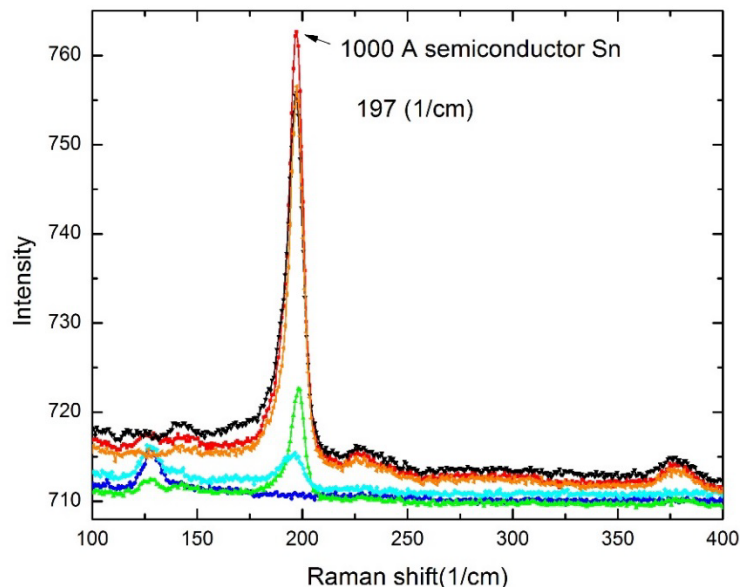
AFM topography maps of the 2 layers confirm that the 200-Å layer shows decreased roughness compared to the 1000-Å layer. The AFM map of the 200-Å layer, shown in Fig. 4, shows regions with peak fluctuations in surface height of around 30 nm surrounded by larger areas with height fluctuations less than 5 nm.



**Fig. 4** Color-coded AFM map of the surface of a 200-Å layer of  $\alpha$ -Sn

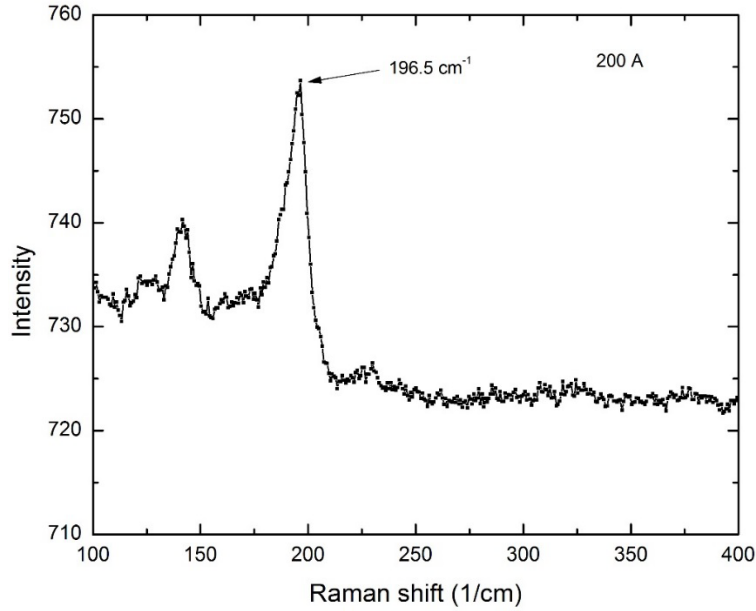
Raman scattering spectra from different points on a 1000-Å layer of  $\alpha$ -Sn are shown in Fig. 5. The color of the various Raman spectra in Fig. 5 corresponds with the color of the crosses in Fig. 3, which indicate the position of the incident laser light. We observe a prominent Raman scattering signal at  $197.3 \text{ cm}^{-1}$  at several measurement points on the 1000-Å layer of  $\alpha$ -Sn, which agrees with previous results<sup>8,11</sup> and confirms the growth of slightly strained epitaxial  $\alpha$ -S on the CdTe buffer layer. The lineshape of the Raman signal for the 1000-Å layer of  $\alpha$ -Sn is nearly symmetrical with respect to the peak energy and its full width at half maximum (FWHM) is constant across the layer at approximately  $9 \text{ cm}^{-1}$ . The Raman scattering signal from the bright spot on the 1000-Å layer of  $\alpha$ -Sn, denoted by the blue cross in Fig. 3, is shown by the blue plot in Fig. 5. The data from the bright spot show the absence of the  $197.3\text{-cm}^{-1}$   $\alpha$ -Sn Raman peak, a reduced

background, and a Raman signal with peak energy at  $128\text{ cm}^{-1}$ , which is attributed to tin oxide. Since the Raman scattering measurements are carried out on the as-grown unpolished samples, the background signal due to diffuse Raleigh scattering from the surface varies with the surface roughness.



**Fig. 5 Raman scattering spectra from a 1000-Å layer of  $\alpha$ -Sn**

The absence of the  $197.3\text{-cm}^{-1}$  Raman peak and the reduced background signal from the bright spot confirms that the tiny bright spots on the 1000-Å layer of  $\alpha$ -Sn are metallic,  $\beta$ -Sn. The Raman scattering spectrum from the 200-Å layer of  $\alpha$ -Sn, shown in Fig. 6, exhibits a peak energy at  $196.5\text{ cm}^{-1}$ , a broadened asymmetrical lineshape with a FWHM equal to  $14\text{ cm}^{-1}$ . The data clearly show that the 200-Å layer of  $\alpha$ -Sn is epitaxial even though the mechanism for the decrease in peak energy and the increased linewidth are still under investigation. The data in Fig. 6 also show that the 200-Å layer of  $\alpha$ -Sn facilitates observation of a larger CdTe longitudinal mode phonon Raman scattering signal at  $141.7\text{ cm}^{-1}$  from the underlying CdTe buffer layer. Density functional theory calculations of the Raman scattering peak energy for bulk  $\alpha$ -Sn show good agreement with the experimental results.



**Fig. 6** Raman scattering spectrum from a 200-Å layer of  $\alpha$ -Sn

#### 4. Conclusion

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Thin layers of single-crystal epitaxial semiconductor  $\alpha$ -Sn were grown by MBE on CdTe substrates. X-ray diffraction and Raman scattering measurements confirm that the thin layers of  $\alpha$ -Sn are slightly strained, which supports theoretical predictions that  $\alpha$ -Sn is a 3-D TI. Future studies will aim at the growth of  $\alpha$ -Sn with improved transport characteristics using high-quality CdTe buffer layers, studies of the 3-D TI characteristics of  $\alpha$ -Sn, and the MBE growth of stanene.

## 5. References

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## List of Symbols, Abbreviations, and Acronyms

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2-D	2-dimensional
3-D	3-dimensional
AFM	atomic force microscopy
CdTe	cadmium telluride
FWHM	full width at half maximum
RHEED	reflection-high-energy-electron-diffraction
SnTe	tin-telluride
Te <sub>2</sub>	tellurium dimers
TI	topological insulator
$\alpha$ -Sn	semiconductor tin

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